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J.R. Fisher and S.D. Meyer (Primex), "The Design and Development of the MR-510 Arcjet Power Conditioning
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AIAA-98-3630

THE DESIGN AND DEVELOPMENT OF THE MR-510 ARCJET POWER CONDITIONING UNIT

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ABSTRACT

PRIMEX Aerospace Company's MR-510 hydrazine arcjet system has been successfully flight qualified for use on Lockheed Martin Corporation's A2100TM communication satellite bus and is currently flying on six spacecraft. The MR-510 arcjet power conditioning unit (PCU) is a key element of this system. It provides the required high voltage start pulse and conditioned power to four 2 kW arcjet thrusters (operated two at a time) for north/south station keeping orbit maneuvers. The PCU draws up to 4.4 kW of power from the satellite's power bus and provides the command and telemetry interface utilizing a bi-directional serial data bus. The MR-510 arcjet PCU utilizes an N+1 redundancy and cross strapping topology. This topology allows one PCU to perform the same functions that required four separate PCUs on previously developed arcjet systems, resulting in an overall reduced weight. A description of the PCU design is provided along with a review of the qualification test sequence and results. On-orbit performance on the first four A2100TM satellites has been nominal, with all indicators pointing to operation of the MR-510 arcjet system as designed and tested.

INTRODUCTION

The MR-510 Arcjet System (AJS) is the third generation arcjet system designed for North/South station keeping on geosynchronous communication satellites. The first flight qualified arcjet system, the MR-508 AJS,^{1,2} was flown on the three inaugural satellites (10 year nominal mission) on Lockheed Martin Corp.'s Series 7000 spacecraft. This system was first deployed on orbit in December 1993.

The second generation system, the MR-509 AJS,³ was optimized for longer life (13 years) and used the same PCU design, with minor updates. This system is currently operating on-orbit on eight of Lockheed Martin Corp.'s Series 7000 satellites.

The MR-510 AJS was developed to have both longer life and higher performance than its predecessors along with having aggressive weight and cost reduction goals. The MR-510 arcjet thruster was successfully qualified for a 15 year mission demonstrating 325,776 lb-sec total impulse (1730 hours) with a mission average specific impulse of 592 sec. The MR-510 PCU design also accomplished these objectives by incorporating the functionality previously contained in four separate MR-508/9 type PCUs into a single electronics box. This PCU provides conditioned power to any two of the four AJTs simultaneously, as selected by the spacecraft. Figure 1 shows a complete shipset of the MR-510 AJS which consists of 4 arcjet thrusters and cable assemblies and one PCU. Details of the MR-510 arcjet thruster and cable assembly qualification were published in an earlier paper.⁴

The MR-510 AJS was first deployed on-orbit on the Lockheed Martin Corp.'s A2100 satellite in September of 1996. At present there are six systems of the new design on orbit, with each of the systems performing as expected.

The PCU handles all input and output power switching as well as the power conversion and control necessary to operate the AJTs. An N+1 redundancy and cross strapping topology was extensively utilized to provide single point fault tolerance, resulting in an overall increase in the AJS calculated reliability when compared to the previous AJS configurations. The PCU typically provides 2 kW of power to each of two AJTs during a station keeping firing for a total of 4 kW of output power. The PCU's operating efficiency varies between 91.2% and 93.6% at 4 kW of output power depending on the AJT's operating voltage and the spacecraft interface temperature. Typical operating efficiency is approximately 92% during normal station keeping firings. The PCU is controlled from the

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spacecraft primarily via a bi-directional serial data link. In addition, there are discrete relay drive commands, along with analog telemetry outputs.

PCU ELECTRICAL INTERFACES

Table 1 identifies all of the PCU's electrical interfaces including power, command, and telemetry. The A2100 spacecraft's 70 volt regulated power bus provides input power to the PCU. There is a single power interface to the spacecraft for the PCU, which is protected against faults by using double insulation techniques and fusing to isolate sections in the event of an electrical short. When the PCU is operating at full power it supplies 4 kW of output power and draws approximately 65 A of input current. To avoid fault propagation in the event of a spacecraft power system anomaly, the PCU will shut off if the voltage of the input power bus falls below approximately 65 volts.

Latching relays are used between the spacecraft power bus and the PCU for each of the two auxiliary power supplies and the three main power converters. The spacecraft provides the pulsed drive commands for these relays. The auxiliary power converters are powered up first to ensure that negative gate bias voltage is present on the main power switches and to allow pre-charging of the filter capacitors on the power converters to reduce inrush current when closing the converter input relays. The converter input power is switched with relays to reduce the time that the converter is powered up. This increases reliability and allows faults to be cleared in the power converter before the solar arrays are fully deployed.

The auxiliary power supply relays have auxiliary contacts to indicate whether the relay contact is in the open or closed position. The spacecraft uses these discrete telemetry outputs to verify that the relay command was sent and properly acted upon.

Analog telemetry outputs are provided for each of the four arcjet thruster operating voltages and current outputs from the three power converters. There is also an additional analog telemetry output for the negative bias supply for the main power hybrid gates. This supply will back up the auxiliary power supply in the event of a failure in one of the auxiliary power supplies after the gate threshold has been depressed due to total dose radiation effects.

Table 1. PCU Electrical Interfaces

Type	Name	Function
Power	Main Input Power	Main power for PCU (+ 70V, - 70 RTN)
	Output AJT Power (Qty = 4)	Start pulse, arc stabilization current profile and constant power output
Command	Aux P/S On (Qty = 2)	Close command for each auxiliary P/S input relay
	Aux P/S Off (Qty = 2)	Open command for each auxiliary P/S input relay
	Converter On (Qty = 3)	Close command for each power converter's input power relay
	Converter Off (Qty = 3)	Open command for each power converter's input power relay
	Set Power Level (Qty = 3)	Sets output power level for each converter
	Set Configuration	Configures the output select relays to one of 16 preset configurations
	Check (Qty = 3)	Enables each converter to generate a low power output voltage
	Run (Qty = 3)	Generates a start signal from the appropriate converter
	Stop (Qty = 3)	Turns off the appropriate converter
	Lock	Prevents configuration changes to the output select relays
	Unlock	Allows configuration changes to be made to the output select relays
	Standby	Forces all converters to standby mode
	Bus Address	Verifies address of each serial data bus
Telemetry	Output Voltage (Qty = 3)	Output voltage telemetry for each of the 4 AJTs
	Output Current (Qty = 3)	Output current telemetry for each of the three power converters
	Negative Gate Bias	Output voltage telemetry for Negative Gate Bias Supply
	Aux P/S On/Off (Qty=2)	Indicates position of each Aux P/S input relay
	Temperature (Qty = 6)	Temperature of each power converter's base and power transformer
	Data Bus Telemetry	Provides 64 status bits that define the PCU's condition

The PCU communicates to the spacecraft over a redundant bi-directional serial data bus. The data link is a differential 5 V interface with separate data in, data out, enable and clock lines. The data link interface logic is implemented in a field programmable gate array (FPGA) in the PCU. Sixty-four status bits are available over the data bus that provide status of the PCU's operational mode and allows fault detection and isolation capability.

The output power interface to each of the four thrusters is made through a custom high voltage tri-axial cable and connector. The outer shield connects between the PCU chassis and the thruster anode and provides a low loop area return path for conducted emissions from the thruster and the arc. The inner shield provides the anode power return with the center conductor carrying the cathode voltage. The PCU output voltage will vary from 0 to -4,000 V over the full range of operating modes. The output current can reach a maximum of 20 A to each of the two operating thrusters. The PCU is qualified over a steady state output voltage range of -105 to -134 V. The PCU regulates output power during steady state operation and has four commandable output power levels between 1500 and 2000 W per output. The output power regulation is very tightly controlled with less than 0.5 percent variation over the entire range of temperatures and input and output voltages.

PCU ENVIRONMENTAL INTERFACES

The PCU was designed to meet environmental requirements typical of a 10 to 15 year duration geosynchronous communication satellite mission. These environments included random and sine vibration, acceleration, and vacuum operation over a broad temperature range. In addition, the PCU was designed to operate under total dose radiation and single event effect environments. The PCU is mounted to the satellite's equipment panel using mechanical fasteners in conjunction with a thermally conductive bonding material for temperature control.

ELECTRICAL DESIGN DESCRIPTION

The PCU's architecture was largely driven by the requirement for a 0.9995 probability that the diagonal pairs of thrusters will operate successfully. This probability of success includes the arcjets, cables and the PCU. To achieve this it was necessary to develop a single point fault tolerant system. Figure 2 shows the functional block diagram illustrating the system architecture. All electrical components utilized are "S"

quality level or equivalent and were selected to be compatible with the PCU's radiation environment.

System Design Description

The PCU has three main power converters that provide up to 2 KW of power to an arcjet thruster. Early in the development program, trade studies were performed to determine the optimal size and number of power converters within the PCU. Results of this study showed that from an overall system perspective, utilizing three, 2-kW modules provided the least complex and lowest mass and cost approach. This was largely driven by the quantity of electrical components that were required using this approach as compared to configurations that utilized a larger number of lower power converters. Each power converter's functional block includes a start circuit for ignition of the thruster and the control circuitry necessary for starting the arcjet thrusters. The high voltage circuitry utilized to generate the start voltage is physically located on the -107 output select circuit card assembly (CCA). Two of the power converters are used during a typical station-keeping maneuver with the third as a standby redundant unit. Cross strapping allows any pair of power converters to be utilized with any two of the four thrusters. The output select portion of the circuitry connects the outputs of the power converters to the active thruster pairs. The arcjet returns are not switched but are connected in parallel.

There are two auxiliary power supplies that provide internal housekeeping and control circuit power and two sets of master control circuitry. The master control circuitry handles the communication to the spacecraft and provides commands to the power converters.

Analog and digital telemetry is used to verify correct operation of the AJS and to aid in reconfiguring which thrusters and PCU functional circuit blocks are utilized.

Input Filtering and Fusing

The PCU utilizes an actively redundant common input filter. This prevents component failures and other credible failures from causing loss of PCU functionality or a power drain to the spacecraft's power bus. The input filter uses techniques such as double insulation, series capacitors and parallel current paths to achieve the fault tolerance necessary. The power output to the power converters, auxiliary power supplies, and the negative gate bias are fused to provide over-current protection. In addition, relays are used to disconnect

the power converters and auxiliary supplies when they are not in use.

Each input power load is fused immediately after the fault tolerant EMI filter. The fuses are a ceramic thick film construction type. These fuses are especially suited for use in space because they clear by diffusion of the fuse element into a glass material. Their characteristics are accurately defined, which allows a de-rating of only 70 percent instead of the more typical 50 percent required by conventional fuses. For the high current power converter fuses, a matched set of 4 fuses are used. This allows a 60 A rating to be achieved from 4, 15-A fuses.

Each auxiliary and negative gate bias power supply input is fused separately. The negative gate bias supply provides an active redundant back-up to the auxiliary power supply in the event of an auxiliary power supply failure. At the end of life, the power hybrid MOSFET gate thresholds become negative from exposure to radiation. Under this condition, it is necessary to have negative gate power to ensure that the hybrids are off. This bias supply prevents secondary failures from occurring if an auxiliary power supply fails.

Auxiliary Power Supply

There are two auxiliary power supplies that provide internal housekeeping and control circuit power. Normally only one is powered at a time. The outputs are combined to provide power to the converter control circuitry and the configuration relays. The master control blocks are powered only from one auxiliary power supply.

Master Control Circuitry

There are two sets of master control circuitry. Normally only one is powered at a time but the command structure is set up to accommodate them if they are powered simultaneously. The master control circuitry handles the communications to the spacecraft, and provides commands to the power converters. Serial data links are used for transferring commands and telemetry information between the master control and the power converter control circuitry. The data links are configured to prevent a single failure such as a short or driver failure from disabling the system.

Power Converter Modules

The power converter must be able to provide constant current over large and rapid voltage changes at

the thruster. This is especially important during the initial thruster startup period when the arc attachment is moving from one location to another on the thruster's anode. The magnitude of the current is controlled with an outer loop that controls power. The power converter modules are push-pull, current controlled, voltage fed converters. The power converter's simplified schematic is shown in Figure 3. The input power is supplied from the input EMI filter. The inputs to the three power converters are in parallel, allowing ripple currents to share the input capacitors. The active power converters are phase shifted from each other to reduce the input current ripple. Each converter switches at 55 kHz. This gives an input ripple frequency of 110 kHz for each converter and the phase shifting causes the frequency to increase to 220 kHz. Fault isolation is provided by input fuses and input power relays. The input filtering at the converter input is provided by ceramic capacitors.

The power converters utilize a push-pull, current controlled converter topology with a push-pull output rectifier configuration. The current control approach utilized results in fast response times of the power converter, allowing it to handle dynamic changes in the thruster voltage and maintain flux balance in the power transformer. The voltage fed push-pull converter has a continuous output current, which is desirable when driving an arcing device such as a thruster. This approach also prevents large current spikes on the output during the switching, minimizing current transients at the AJT.

The main power switches utilize custom power hybrids that use six, N-channel power MOSFETS. The power transformer and interconnects are carefully designed to control inductance. Primary current is sensed for the current mode control using current sense transformers. Fast response of the current control is necessary to accommodate occasional saturation of the transformer that can occur when there is a large voltage change on the thruster. Output current is also sensed using current transformers.

Power converter control is achieved using multiple control loops in conjunction with a state machine that provides the sequencing and logic control. A novel approach was utilized in the power regulation control loop design, resulting in a power regulation accuracy of better than 0.5 percent over the operating temperature, input and output voltage range.

The power converter operates in a constant current mode for the initial two seconds after startup and changes to a constant power mode while ramping to the full output power set point as shown in Figure 4. A

state machine that is implemented using an FPGA provides this sequencing and control. The FPGA for each power converter handles the detailed thruster startup and shut down sequencing and prevents potentially damaging modes of operation from occurring. It also interfaces with the master control FPGA to configure the PCU to run the commanded thruster pair from the active power converter modules.

Start Circuitry

The MR510 PCU uses a patented³ parallel AJT starter method that provides a longer duration start pulse than is practical with the conventional fly-back starter methods. This method also allows the output filter inductor to be smaller since it only needs to handle the output ripple filtering. In the parallel starter, the output inductor is not required to store the energy necessary to raise the output cable capacitance to the breakdown voltage and still be able to keep the output current above the initial critical current level. The parallel starter's simplified schematic is shown in Figure 5 and a state diagram of its operational sequence is shown in Figure 6.

The operation of the starter is controlled by the power converter's state machine. The first action is to open the diode bypass relay S2. The second action is to charge the converter output inductor. To accomplish this, a current path is provided through S1, D1 and D2. D2 is a transient suppression diode. Approximately 10 ms are allowed for charging of the output inductor.

The next step is to generate the high voltage necessary for breakdown of the arcjet thruster. This high voltage is generated with a small ferrite core transformer that operates in the forward direction. When the cathode is driven negative by T2, D3 is reverse biased, allowing a high voltage pulse to be generated. D3 is a string of high voltage, 1 A diodes. When the arcjet breaks down, the voltage drops below the clamp voltage of the shunt path and inductor current is diverted into the arc to sustain the discharge. The breakdown of the thruster is detected by sensing current delivered to the arcjet. As soon as current is detected, the shunt path is turned off by opening S1 and the start drive is terminated by opening S3. The relay, S2, used to bypass the series diodes is also closed at this time. This novel circuit design approach provides a highly capable, low weight AJT start circuit.

Bubble Tolerance Circuit

The MR-510 PCU incorporates the same bubble tolerance features successfully demonstrated on the

MR-509 PCU. The PCU incorporates circuitry that detects the presence of bubbles in the hydrazine propellant as they pass through the thruster assembly and modifies the PCU's output to prevent the thruster from going out and avert damage to the AJT. On-orbit telemetry indicates that the performance of this feature on the MR-510 PCU has been nominal, working exactly as designed and previously demonstrated.

MECHANICAL DESIGN DESCRIPTION

The PCU was designed to be modular to minimize assembly time and facilitate circuit card level testing. The major drivers in the mechanical design of the PCU included thermal management, vibration, mass, electrical bonding, high voltage insulation, radiation shielding, and over 2,400 electrical components that were accommodated. In addition, the requirement for single point fault tolerance significantly impacted the design in those areas that required double insulation practices. Figure 7 shows the major subassemblies that are contained in each PCU.

The PCU was designed to minimize the amount of hand wiring and soldering. An example of this is the rigid-flex-rigid circuit card assembly used for each of the three power converter control -103 CCAs which utilize standard PCB style plug-in connectors that eliminated over 300 interconnects that would have otherwise been hand wired.

Custom Power MOSFET hybrids were utilized for the main power switches to minimize the amount of volume and mass required for these components. Each hybrid contains six MOSFET die in parallel which is equivalent to approximately 14 discrete TO-254 packaged MOSFET devices. These devices allowed the main power converter module, as shown in Figure 8, to achieve a power density greater than 1100 W/kg.

Thermal management design considerations required special attention during the development of the PCU due to the maximum allowable concentrated heat flux between the PCU base and the spacecraft interface panel. From an overall electrical performance standpoint, the primary power components in the main power converter prefer to be in close proximity to one another. Since these components also dissipate a majority of the power dissipated in each converter, the resulting concentrated heat flux must be efficiently spread over a much larger area on the PCU base to avoid excessive point heat flux levels at the spacecraft interface. This was accomplished by incorporating additional heat spreading material in the PCU base and locating the highest heat flux zones directly over the

heat pipes that are embedded in the spacecraft's equipment panel. The thermal design of the PCU was optimized using finite element analysis to ensure that adequate heat conduction paths were provided for all electrical components.

The structural design of the PCU was optimized using finite element analysis to predict the dynamic response of each circuit card assembly. This analysis helped determine the number of structural fasteners and stiffness required. In addition, individual components were analyzed to ensure component lead stresses were not excessive and to identify those components that required structural bonding. The mass of the MR-510 PCU is 14.98 kg.

EMI radiated emission levels were minimized by ensuring low impedance electrical bonding between the PCU housing and cover and the appropriate connectors based on the utilized grounding scheme. On each of the four output connectors, the connector back shell and the adjacent mounting surface on the cover were plated with nickel to obtain very low impedance which reduced the overall radiated emission levels.

All high voltage circuitry associated with the start circuit is contained on the -107 CCA. Special attention was paid to all circuit routings in this area to ensure that adequate spacing was provided between high voltage circuit interconnects and other circuitry. In addition, all solder joints in the high voltage path are rounded and smooth, resembling domes, to avoid sharp points that can act as discharge initiation sites. As a secondary precaution, void free insulation methods were utilized to prevent corona glow or discharges from forming and include the use of a vacuum deposited conformal coating material known as paralyne. The PCU enclosure was vented, using multiple vent holes in the side walls and cover to ensure that the internal pressure of the PCU quickly comes to equilibrium with the external vacuum environment. This venting prevents operation under partial pressure conditions that promote corona type electrical discharge.

The PCU was designed to meet the specified total dose radiation environment using a combination of components that were procured with a guaranteed level of radiation hardness along with varying the enclosure wall thickness, depending on the corresponding external environment, to provide adequate shielding thickness.

QUALIFICATION TESTING

Qualification testing of the MR-510 PCU consisted of the test sequence shown in Figure 9. All testing was

successfully completed and demonstrated full compliance to all performance specification requirements.

High Voltage Corona Test

The high voltage portion of the start circuit, which is located on the -107 assembly, was tested for corona discharge. Testing was performed under vacuum level conditions at 70 C and utilized a 5 kV potential. The test demonstrated that less than 100 pC of corona energy was generated under all conditions.

Full Functional Electrical Test

Full functional electrical tests were performed throughout the qualification test sequence to ensure the unit successfully passed each prior test. Each test verified the PCU's response and functionality to all commands between the PCU and the spacecraft, proper telemetry signal outputs from the PCU, all electrical interfaces between the PCU and the AJT, and verification of isolation and grounding. In addition, testing verified the functionality for each of the 32 configurations that the PCU can be set to that represent different combinations of power converters, output connectors, and command interface circuitry. Operating efficiency was also measured at four different output power set points over the entire input/output voltage range.

To facilitate automated testing of the PCU during both the development and production of the MR-510 PCU, a PC based control and measurement system (CAMS) was developed.⁹ This test system consists of a single bay rack that contains a 80486 based PC, IEEE 488 multiplexing and discrete I/O devices, a DC power supply, a DMM, a digital oscilloscope, and custom interface circuitry. An extensive graphic user menu driven interface was developed using Visual Basic 3.0 with a custom dynamic link library created using Borland C++. This approach allowed the automation of many of the testing sequences required and supported fully automated burn-in and life testing.

Vacuum Thermal Bench Testing

The PCU was instrumented with approximately 40 thermocouples that were located on those electrical components that had the least amount of temperature margin relative to their derating limits. Testing was performed under vacuum conditions with the PCU mounted to a fluid cooled, temperature controlled cold plate. The PCU was operated under various input/output voltage conditions with a cold plate

temperature of 73 C. Thermocouple data was logged throughout each test and later converted into the appropriate component hotspot or junction temperature. Testing verified that all electrical components were below their derated temperature limits and confirmed the PCU's operating efficiency was within the specified limit of 90.7 percent at worst case temperature and voltage conditions.

Electromagnetic Interference Testing

The PCU was tested for radiated and conducted emission levels and radiated and conducted susceptibility. The PCU successfully demonstrated compliance to a tailored version of MIL-STD-461C for both conducted (CE-01, CE-02) and radiated emission (RE-01 and RE-02) levels and showed no susceptibility to radiated (RS03) or conducted (CS01, CS02, CS06) electromagnetic fields.

Electro Static Discharge Testing

The PCU was tested for ESD sensitivity by injecting 40 A of pulsed current through the enclosure. The PCU successfully operated while subjected to this environment.

Vibration Testing

The PCU was subjected to both sine vibration (10 - 100 Hz, 7 to 20 g peak) and random vibration (20 to 2,000 Hz, 17.2 grms, 2 minutes) testing in all three axes with power applied to the input connector to simulate launch conditions. Post vibration visual inspection and full functional electrical testing demonstrated the PCU's ability to meet this level.

Vacuum Thermal Cycle Testing

Vacuum thermal cycle testing consisted of ten ambient-hot-cold-ambient temperature cycles with concurrent electrical performance testing. The PCU was operated under vacuum level conditions while mounted to a fluid cooled, temperature controlled cold plate that was cycled from -34 C to 73 C. A minimum of two hours of operation was accumulated at each temperature plateau along with functional electrical testing. All performance test data was reviewed for compliance to the performance specification and for trending over the ten cycles and was found to be nominal.

The PCU's operating efficiency during vacuum thermal cycle testing is shown in Figure 10. Note that the single converter operational efficiency is higher than the two converter operational efficiency due to the I²R

losses in the common portion of input filter. Output power regulation during vacuum thermal cycling is summarized in Figure 11. The MR-510 PCU demonstrated a very narrow output power regulation range over temperature, typically less than 5 W out of 2000 for an accuracy of < 0.5%.

Burn-In Testing

The PCU was subjected to burn-in testing consisting of 96 one-hour cycles at full load with a two-minute off state between each cycle. Testing was performed under vacuum level conditions at a cold plate temperature of 55 C. Six PCU configurations were utilized during the test that varied the power converter, output connectors, and the command interface utilized. Output voltage, current, and power along with operating efficiency and six internal temperatures were continuously monitored during the performance of this test and all showed nominal results.

Arcjet Thruster Firing

The PCU was tested with one output connected to the MR-510 Qualification AJT and the other to a resistive load simulator. Each of the three power converters was utilized to fire the arcjet thruster twice, while varying the operational mode of the other converter pair and varying which command interface circuit was utilized. This resulted in twelve successful AJT firings that demonstrated all functional elements within the PCU.

Life Demonstration Testing

During the qualification life test of the MR-510 arcjet thruster, an engineering development model MR-510 PCU was used to support the 1,730 hour test which included 1,900 starts. As part of the formal PCU qualification sequence a life demonstration test was performed on the MR-510 qualification PCU which demonstrated the PCU's ability to provide power over a A2100TM, A-class spacecraft for a 15 year mission plus a 50% margin of safety. Testing was performed under vacuum conditions at full power operation and utilized arcjet load simulators. The PCU was mounted to a 55 C cold plate and operated for 1,755 cycles while cycling through six configurations of power converters, output connectors, and command interface circuitry in the same fashion as the burn-in test. Each cycle consisted of a 49-minute on time, and a 6-minute off time resulting in a total operational time of 1,433 hours, with each of the three power converters accumulating 955 hours. Output voltage, current, and power along with operating efficiency and six internal temperatures were

continuously monitored during the performance of this test and showed nominal results. Successful completion of the final full functional test following the life demonstration test concluded the PCU's qualification test sequence.

PRODUCTION STATUS

Currently, twelve MR-510 PCUs have been successfully fabricated and acceptance tested, with additional units in work. Acceptance testing consists of a test sequence similar to that performed during qualification, with the exception of thermal bench, EMI, and life testing, which are not performed on flight PCUs. Six MR-510 AJS are currently on-orbit with all indicators pointing to operation as designed and tested.

CONCLUSIONS

PRIMEX Aerospace Company's MR-510 Arcjet PCU has been flight qualified and is now in use on Lockheed Martin Corp.'s A2100™ communication satellite bus. The PCU provides all command and telemetry interfaces with the spacecraft while supplying conditioned power to each of the four MR-510 AJS, incorporating all system level functionality previously provided by four separate PCUs on earlier deployed arcjet systems. The PCU has demonstrated the ability to withstand all transport, launch, and on-orbit environments specified for the extended satellite mission lifetime of 15 years, which is made possible by the utilization of arcjet system technology.

The first launch and on-orbit operation of the MR-510 AJS occurred in September of 1996. Six A2100™ communication satellites have been launched to date with all on-orbit performance of the arcjet system being nominal. The MR-510 PCU is currently in production to meet A2100™ production requirements.

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REFERENCES

- 1) Smith, R.D., Yano, S.E., Armbruster, K., Roberts, C.R., Lichtin, D.A. and Beck, J.W., "Flight Qualification of a 1.8 kW Hydrazine Arcjet System", AIAA-93-007, September, 1993.
- 2) Skelly, P.T., Fisher, J.R., Golden, C.M., "Power Conditioning Unit for Low-Power Arcjet Flight Application", AIAA-92-3529, July, 1992.
- 3) Smith, R.D., Roberts, C.R., Aadland, R.S., Lichtin, D.A., Davies, K.A., "Flight Qualification of the 1.8 kW MR-509 Hydrazine Arcjet System", IEPC-97-081, 25th IEPC, August, 1997.
- 4) Smith, R.D., Aadland, R.S., Roberts, C.R., Lichtin, D.A., "Flight Qualification of the 2.2 kW MR-510 Hydrazine Arcjet System", IEPC-97-082, 25th IEPC, August, 1997.
- 5) U.S. Patent No. 5,605,039, Parallel Arcjet Starter System, February 25, 1997.
- 6) Nagle, S.M., "A System for the Test of a Space Electronics Device", IEEE Autotestcon '96, September, 1996.

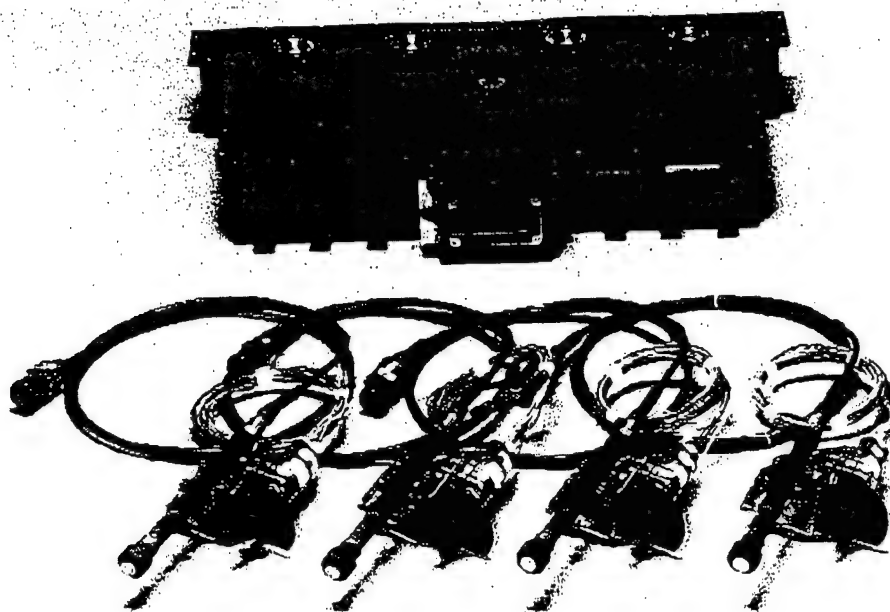


Figure 1. MR-510 Arcjet System (1 Shipset)

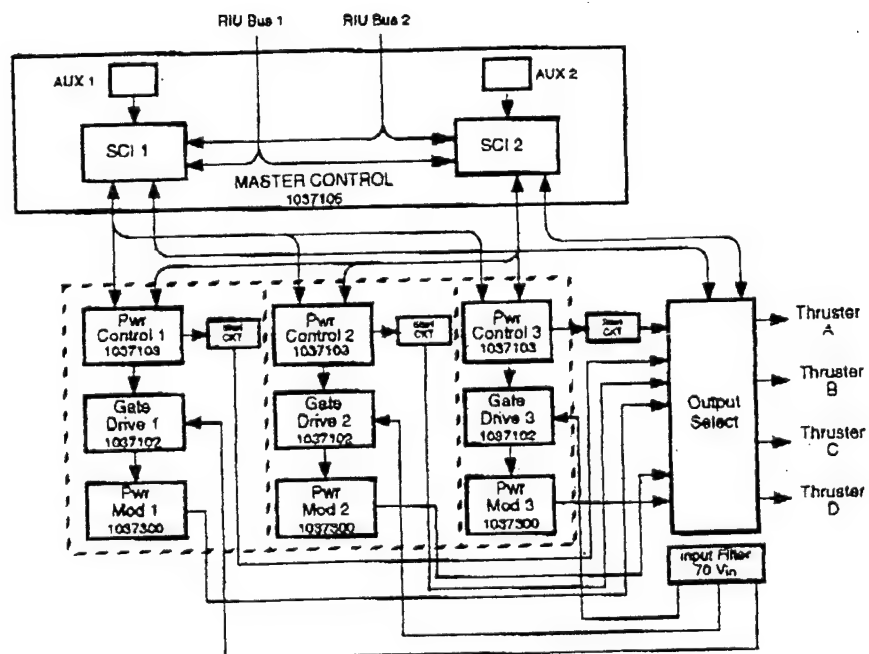


Figure 2. MR-510 PCU Functional Block Diagram

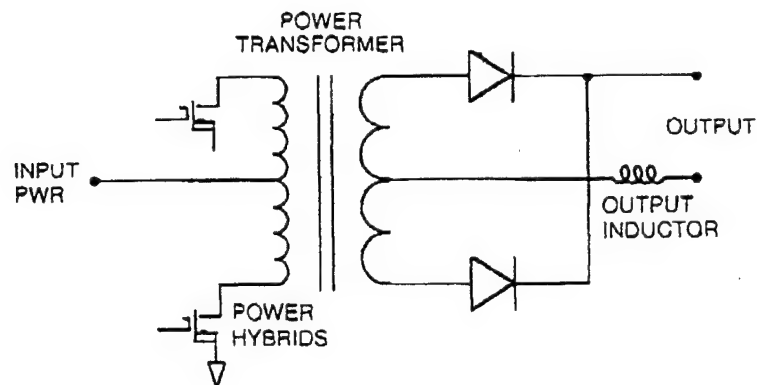


Figure 3. Simplified Schematic of Main Power Converter

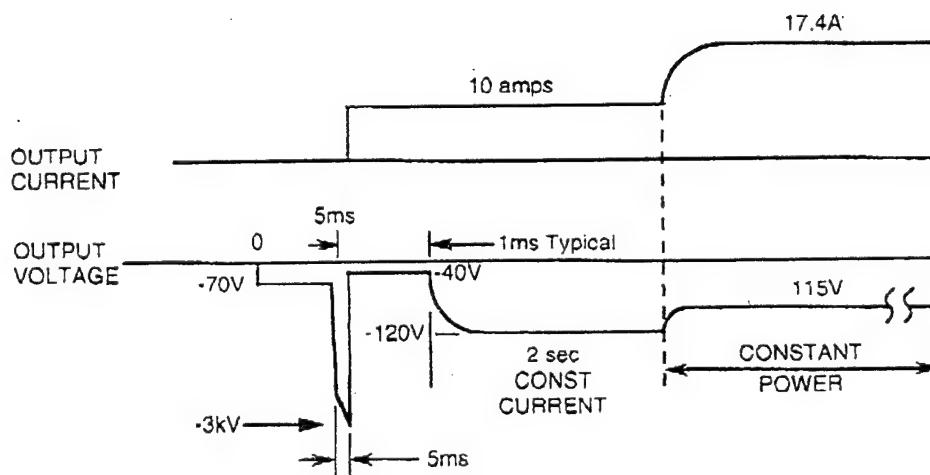


Figure 4. Typical Arcjet Start Sequence

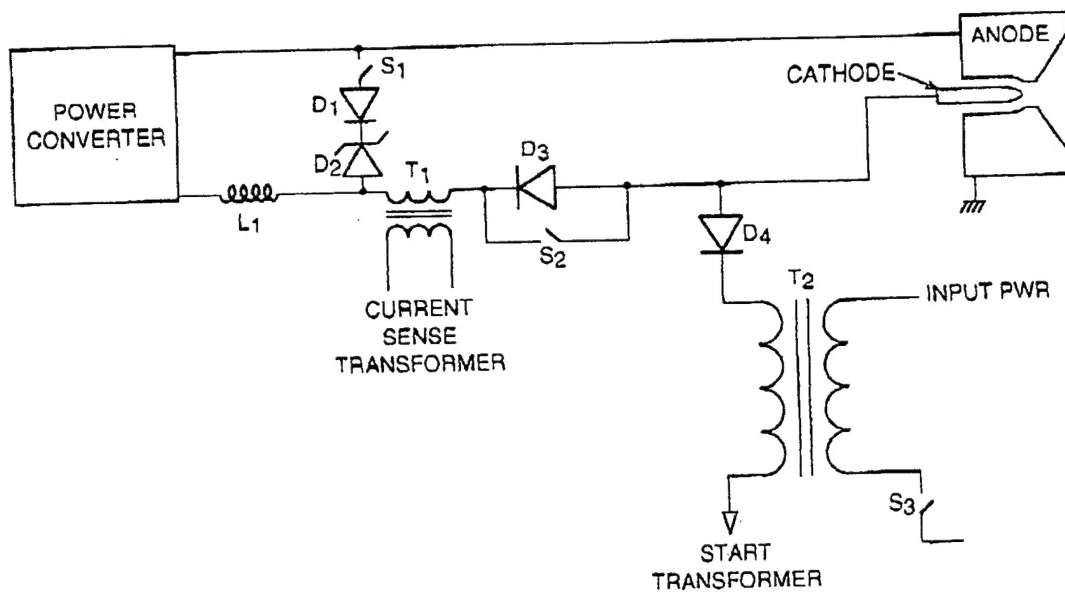


Figure 5. Simplified Parallel Start Circuit Schematic

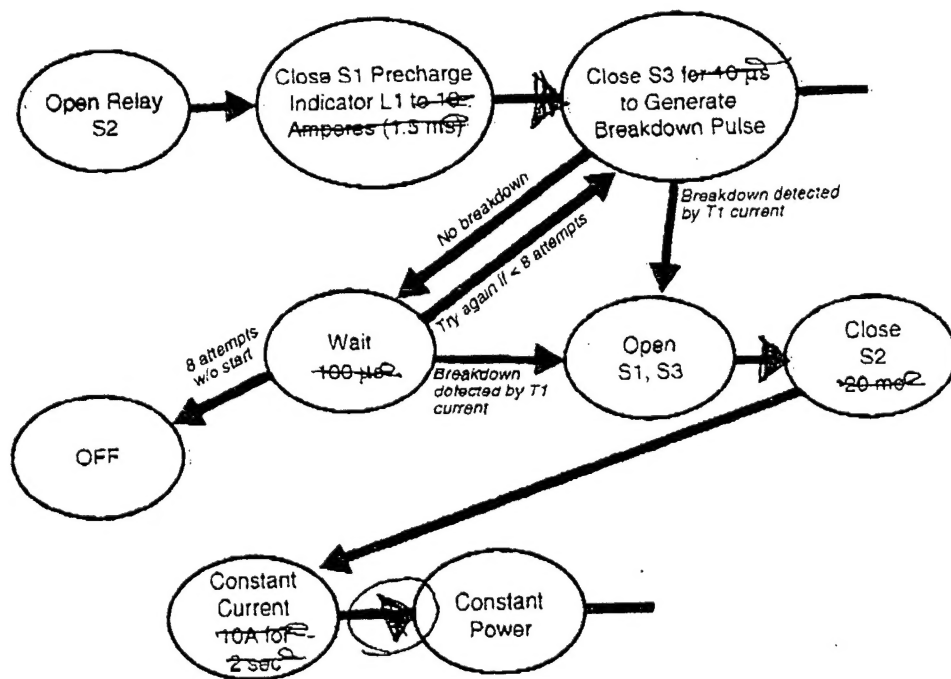


Figure 6. State Diagram for the Parallel Start Circuit

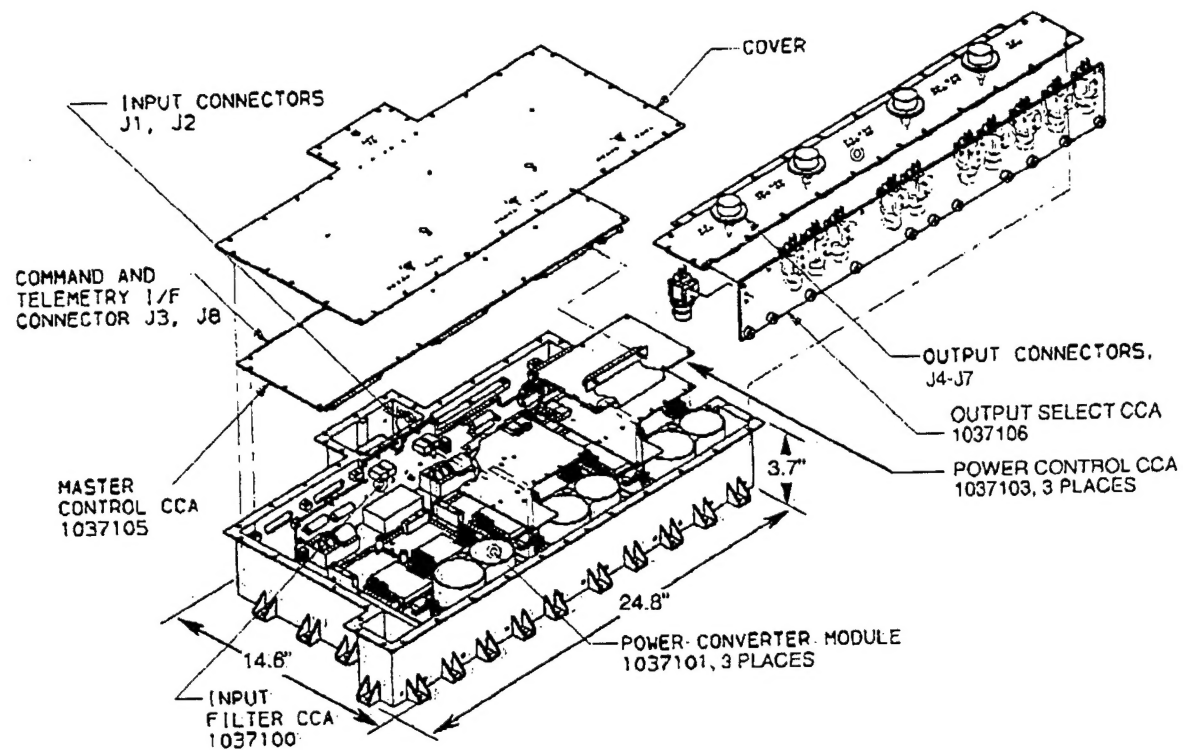


Figure 7. Mechanical Design of the MR-510 PCU

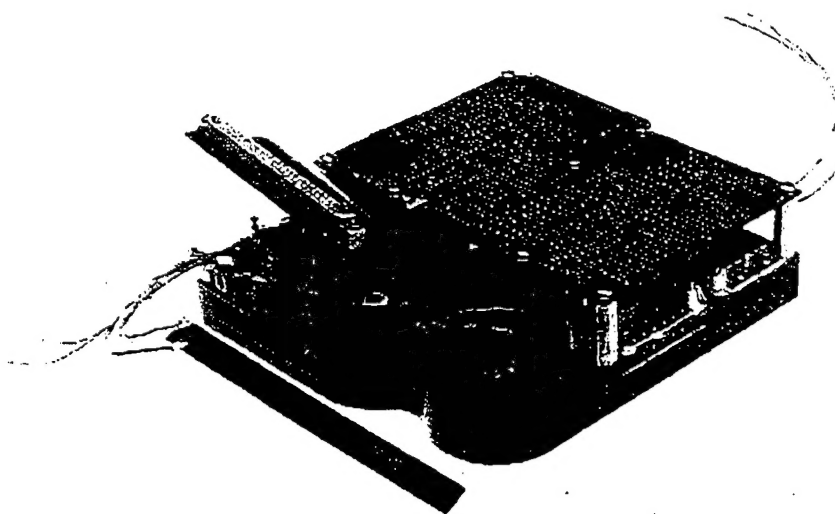


Figure 8. Power Converter Module (1037101)

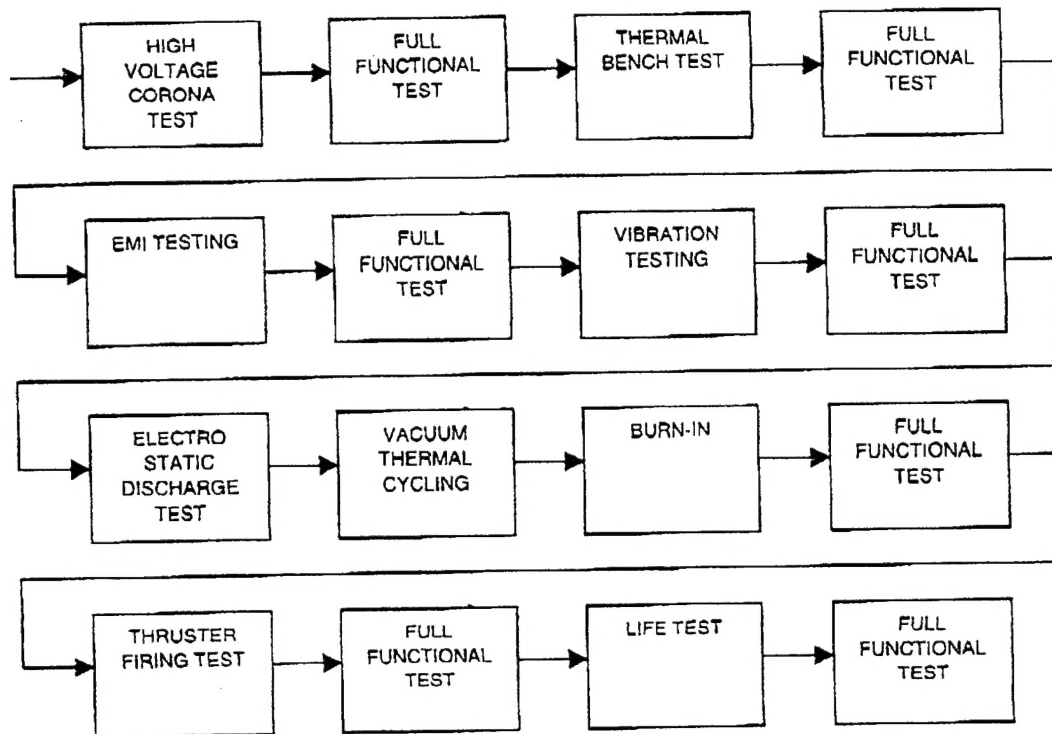


Figure 9. MR-510 PCU Qualification Test Sequence

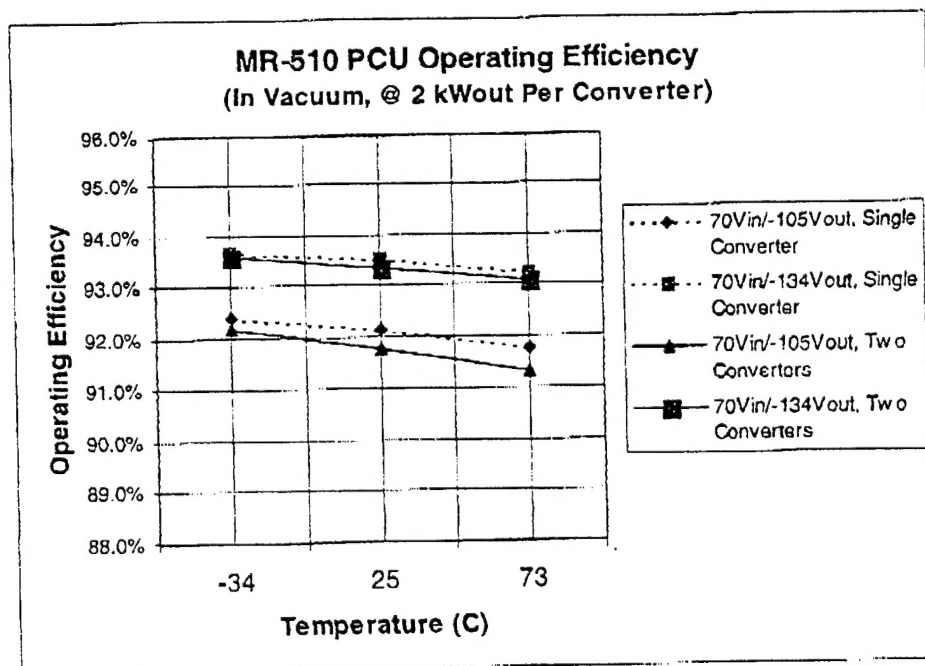


Figure 10. MR-510 PCU Operating Efficiency

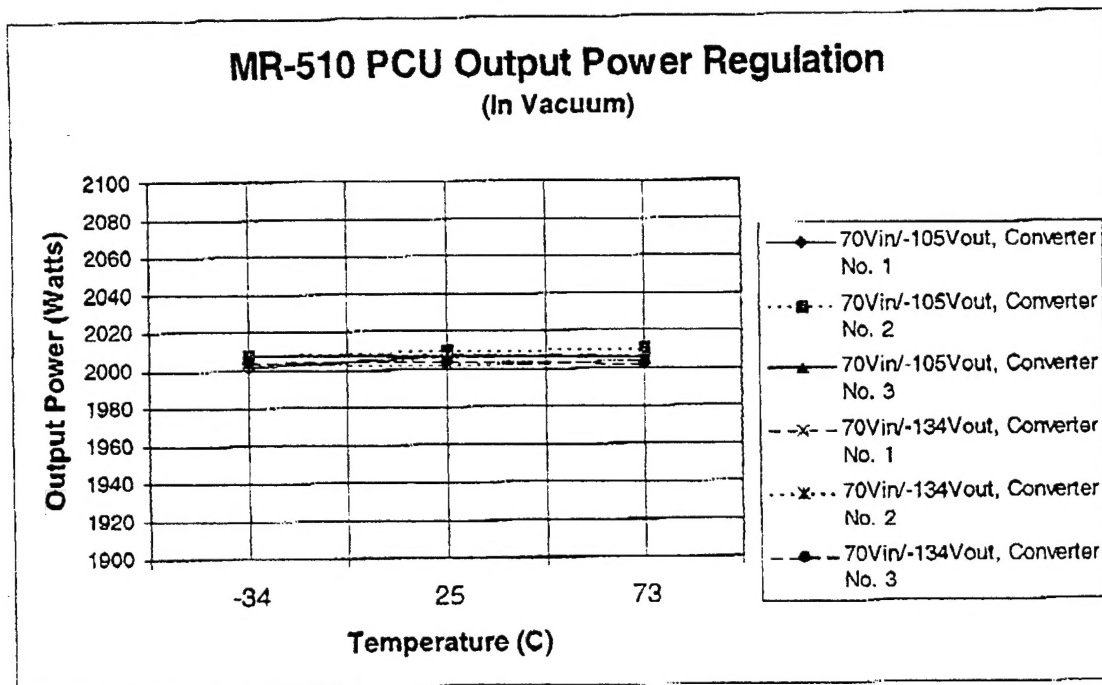


Figure 11. MR-510 PCU Output Power Regulation